

Liquefaction and Storage of In-Situ Oxygen on the Surface of Mars

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Introduction

- In-Situ Resource Utilization (ISRU) is currently baselined for the production of oxygen on the Martian surface in the Evolvable Mars Campaign
 - Over 50% of return vehicle mass is oxygen for propulsion
- There are two key cryogenic fluid/thermal technologies that need to be investigated to enable these architectures
 - High “lift” refrigeration systems
 - Thermal Insulation systems; either lightweight vacuum jackets or soft vacuum insulation systems
- Two studies were performed at the architecture level:
 - Location of liquefaction
 - Trade between insulation performance and cryocooler lift



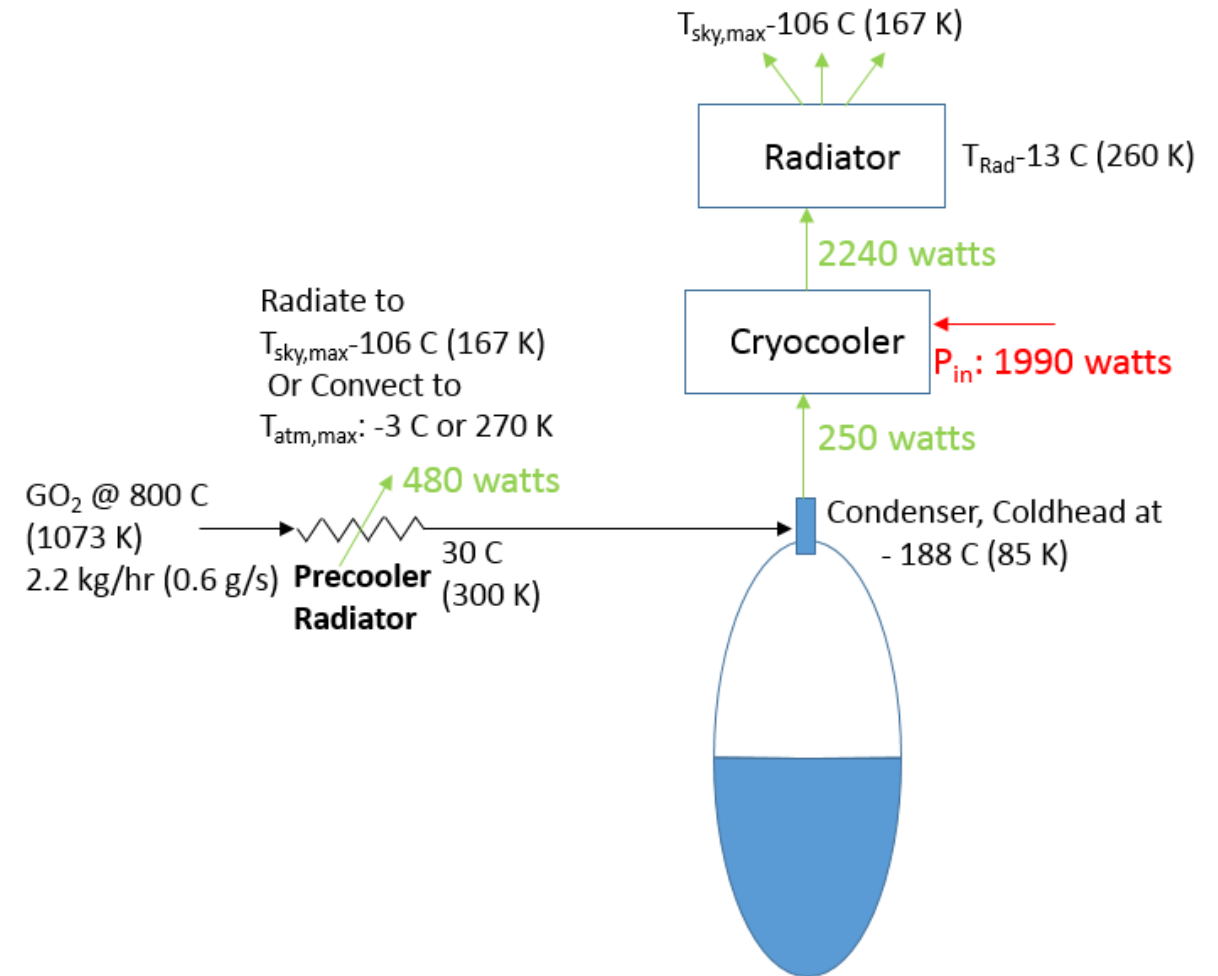
Liquefaction System Overview

- Liquefaction of oxygen on the surface of Mars was investigated to reduce the mass of the return vehicle delivered to Mars
 - Propellant makes up 75% of the mass of the return vehicle from Mars.
 - 75% of the propellant mass is liquid oxygen (55% of return vehicle mass)
- Oxygen is planned to be produced through the electrolysis of carbon dioxide via a solid oxide electrolyzer
- Oxygen then needs to be cooled, liquefied, and stored for durations up to two years
- Oxygen liquefaction locations have been discussed over the years:
 - Directly in the flight liquid oxygen tanks
 - In separate tanks that are brought along solely to perform this function
 - In an flow through heat exchanger

Basic Liquefaction Process

- GO_2 exits solid oxide electrolyzer at 800 °C and needs to be cooled to near Mars atmosphere temperature (30 °C) using a radiator
- GO_2 is further chilled and condensed using a cryocooler
- LO_2 is stored for up to two years before crew arrival/departure

Liquefaction Schematic Using One Cryocooler
(Sized for Full Scale, 2.2 kg/hr)





Oxygen Liquefaction Sizing

- Cryocooler sized based on reverse turbo-Brayton cycle
- Radiators sizing based on worst case Mars environmental temperatures
- Condenser sized based on heat removal rates and gravity driven condensation

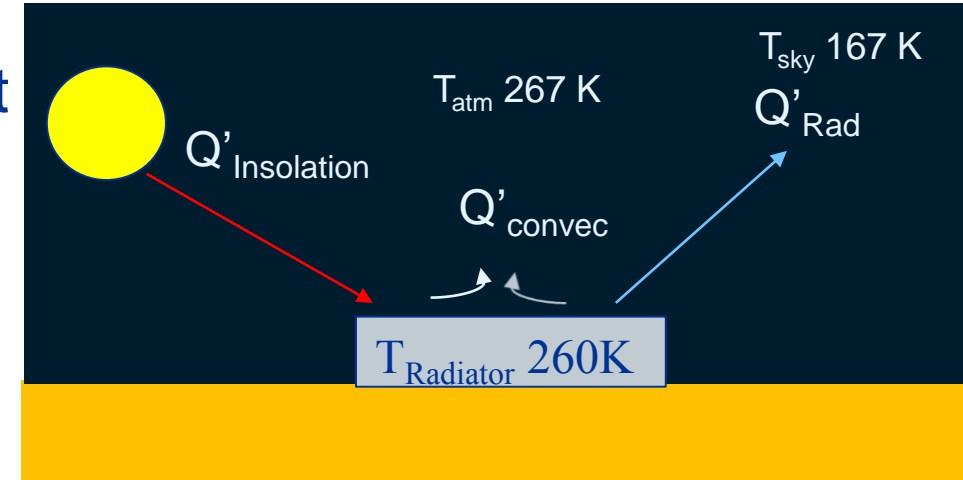
Component	Mass, kg
Cryocooler	63
Radiator	65
Precooler Radiator	6
Condenser	2.5
Total	136.5

Radiator Sizing

- Radiator sized by performing an energy balance on the radiator surface accounting for various heat transfer mechanisms

- Radiation* $Q'_{Rad} = -\sigma\epsilon(T_{Radiator}^4 - T_{sky}^4)$
- Convection** $Q'_{Convec} = H_{nat.conv} \cdot (T_{Radiator} - T_{atm})$
- Solar Insolation $Q'_{Insolation} = Q'_{Total\ Insolation} \cdot \alpha$

$$Q'_{Rad} + Q'_{Convec} + Q'_{Insolation} = Q'_{load}$$



Q'_{rad}	168 watts/m ²
$Q'_{insolation}$	-28 watts/m ²
$Q'_{convection}$	-1 watts/m ²
Q'_{load}	139 watts/m ²
$Q_{required}$	2,250 watts
Area required	16 m ²
Radiator Mass**	65 kg

*Radiator surface assumed to be 5 mil silver Teflon

**Convection assumed to be natural convection across a 2 meter tall vertical plate

***Radiator Aerial density assumed to be 4 kg/m²



Liquefaction Location

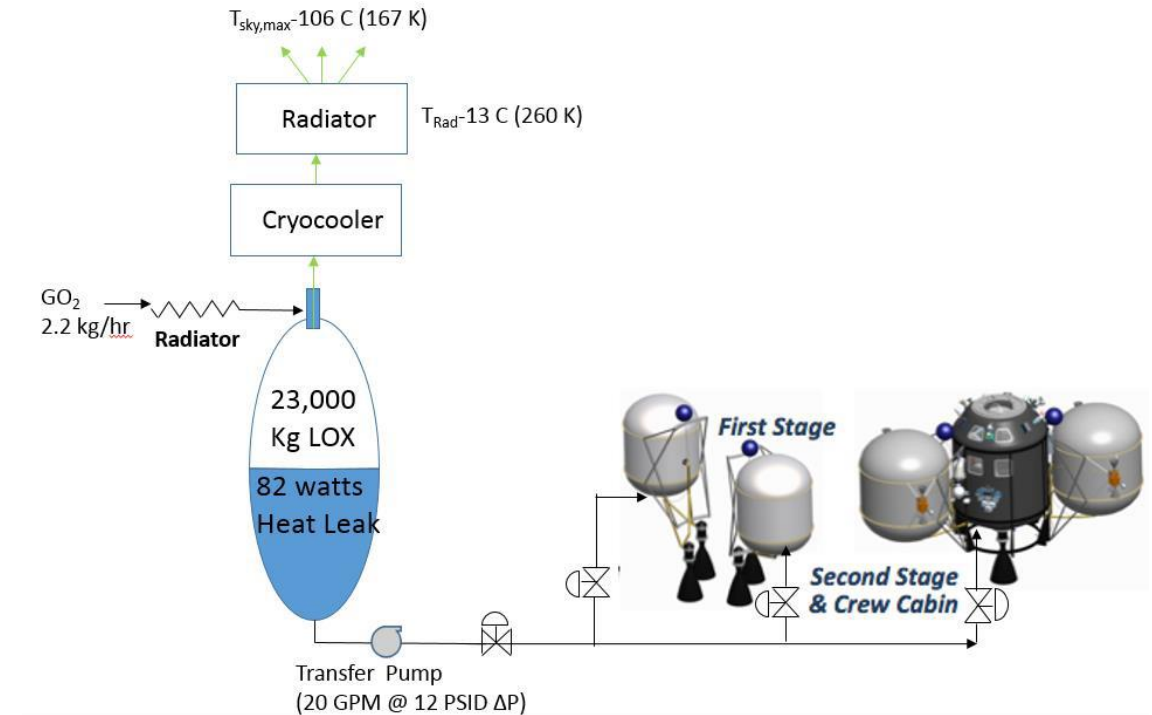
- A. Baseline Option: Liquefy in separate tank
- B. Liquefy inline before MAV tank
- C. Liquefy directly in MAV tank

Assumptions:

- MAV tank already has cryocooler in place to maintain ZBO
- 25% margin added for heat leak to account for thermal uncertainty
- Constant flow of GO_2 from electrolyzer, purification done upstream
- Flow exits pre-cooling radiator at 300 K

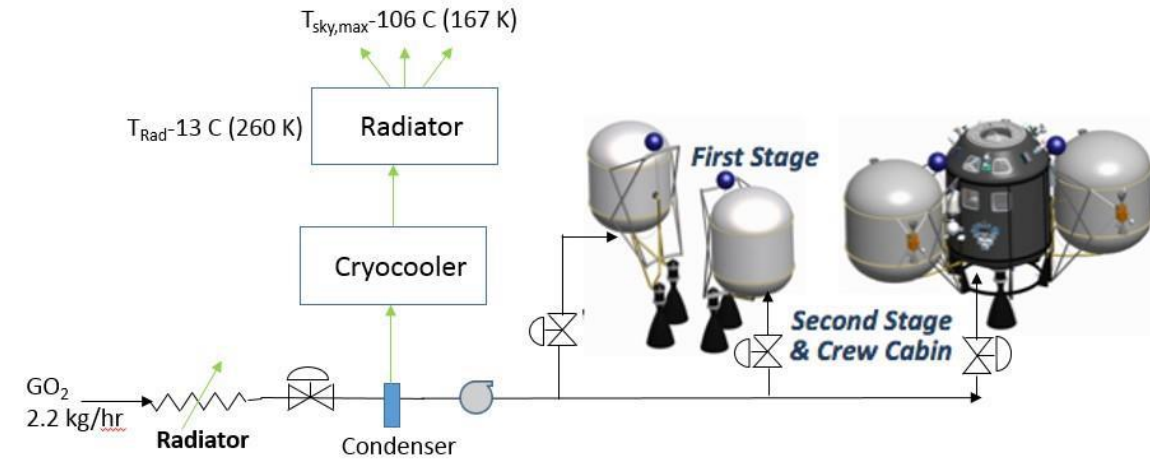
Baseline Option A: Liquefy in Separate Tank

- Liquefaction occurs in separate tank
- Vacuum Jacketed tank sized for one LOX transfer into MAV tanks
 - Tank diameter ~ 3 m
 - L/D ~ 1.25
 - Concept mass driven by transfer frequency



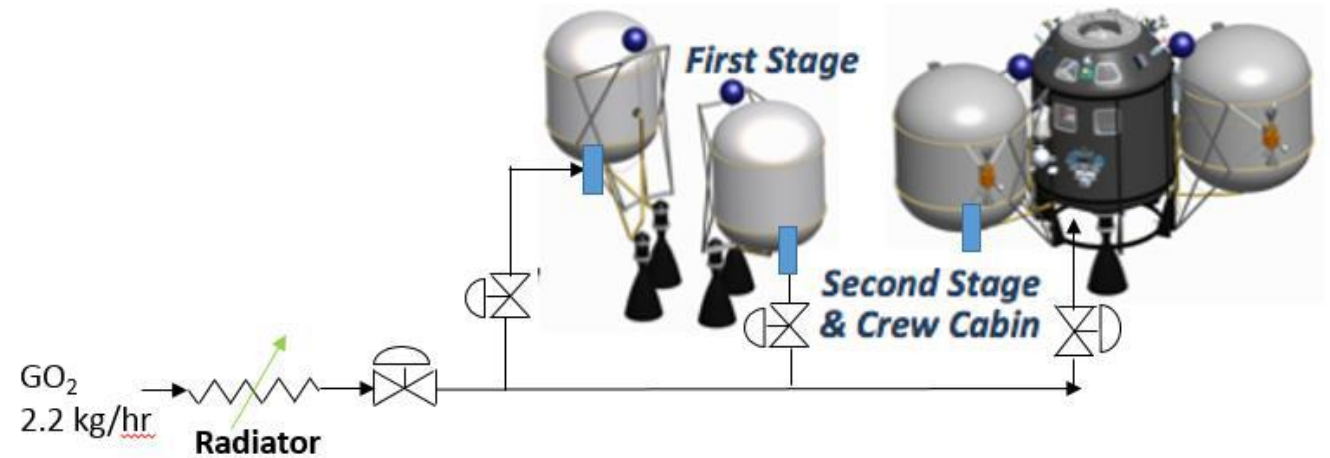
Option B: Liquefy Inline Before MAV Tank

- Liquefaction occurs inline before MAV Tank
- 50' long transfer line between liquefier and MAV tanks
 - Insulation composed of 1" aerogel (100 watt heat leak)
 - Transfer line length drives “parasitic” heat loads



Option C: Liquefy directly inside MAV Tank

- Liquefaction occurs directly inside MAV tanks
- Similar to CPST Tube-on-tank Zero Boil off testing
- Requires increased size of cryocooler on MAV tanks (100 W -> 200 W)
- No mass required for extra tank and lower cryocooler power and mass due to reduced heat leakage





Cryocooler Lift and Power

	Baseline, Option A	Option B	Option C
Cryocooler Lift, watts	410	375	310

	Baseline, Option A	Option B	Option C
Cryocooler Power, watts	3,355	3,530	2,500
Valve Power, watts	100	100	100
Total, watts	3,625	3,630	2,600



Mass Estimates of Options A, B, C

Component	Baseline Option A	Option B	Option C
Cryocooler	100	104	74
Radiator	110	112	80
Tank	450	-	-
Tank Insulation	19	-	-
Vacuum Jacket	115	-	-
Support Structure	225	-	-
Plumbing & Insulation	27	27	3
Condenser	-	3	-
Pump	12	12	-
Valves	10	10	10
Total, kg	1,068	268	167

Notes: Input power assumed to be nuclear and have minimal mass penalty.

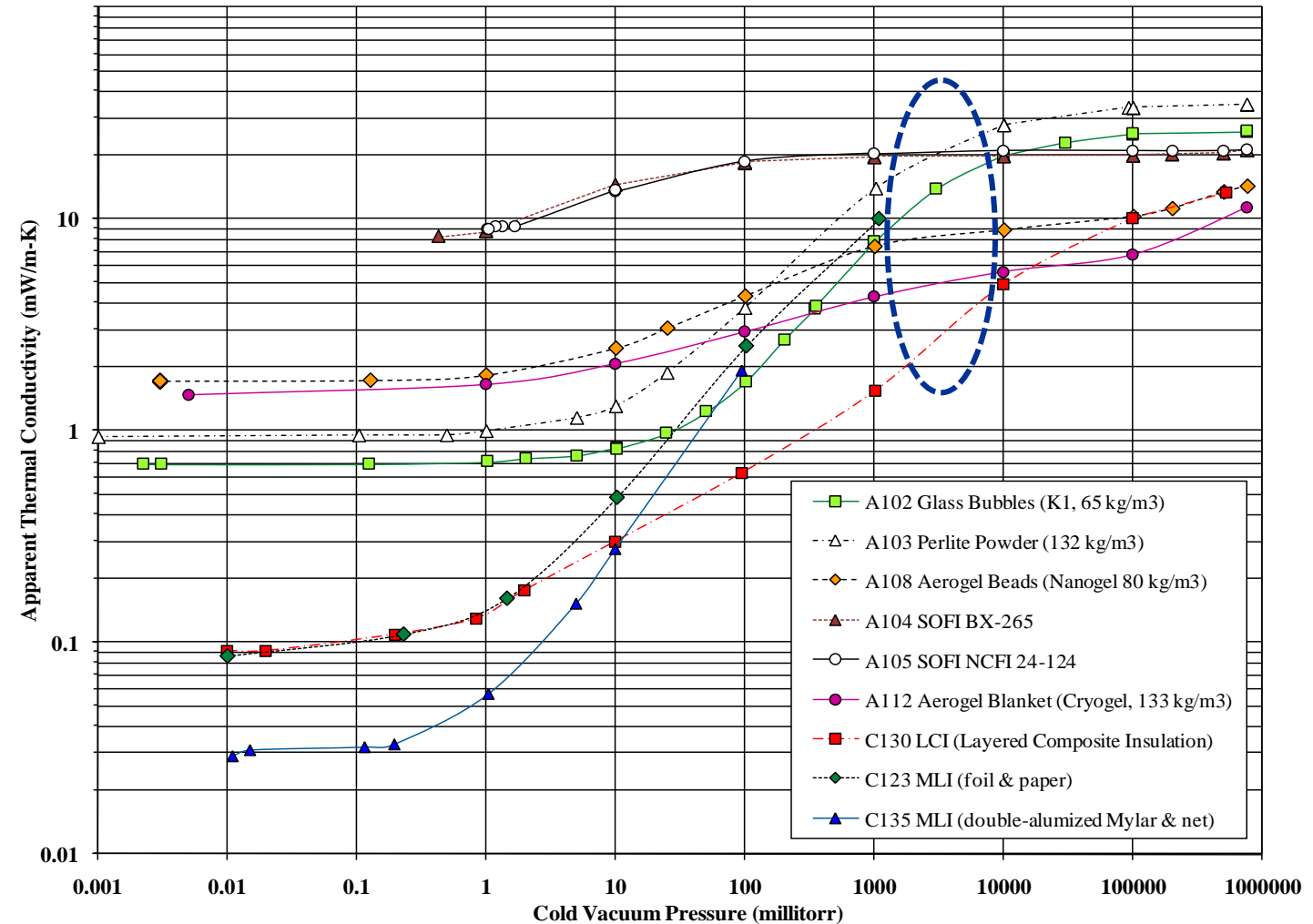


Summary of Results

- Mass for Option B is less than baseline due to not having extra tank but the cryocooler power and corresponding mass is higher due to the continuous heat losses in transfer line
- Mass and power for Option C is less than baseline and option B, eliminating transfer tank and insulated line reduces mass and increases energy efficiency of system(less power).
 - Excess lift on flight tank gives more control of flight tank propellant conditions
- Reducing tank size to support monthly transfers reduces mass to 330 kg for Option A

Insulation Systems On Mars

- Travel to Mars involves three drastically different environments:
 - Earth atmosphere
 - Space vacuum
 - Mars atmosphere
- The average Mars atmosphere is approximately 5 Torr (0.1 psia, 0.6 kPa)
- This is enough gas pressure to cause problems in typical spaceflight insulation systems
- The key to a good cryogenic storage system is a good insulation system
 - Whatever energy makes it into the system is required to be removed by refrigeration
- Need to provide mass targets for insulation system development





Assumptions

- Used Mars Ascent Vehicle (MAV) thermal models and baseline assumptions
 - Initial insulation baseline was Spray On Foam Insulation + Multilayer Insulation
 - SOFI prevents liquefaction/solidification of CO₂ on the tank wall
 - MLI provides thermal protection needed during space transit
 - Environmental temperature of 267 K
 - Oxygen storage temperature of 105 K
- Reverse turbo-Brayton cycle refrigeration system
- Radiators to reject power provided to refrigeration system
- Nuclear power source available, so power input not a driving issue



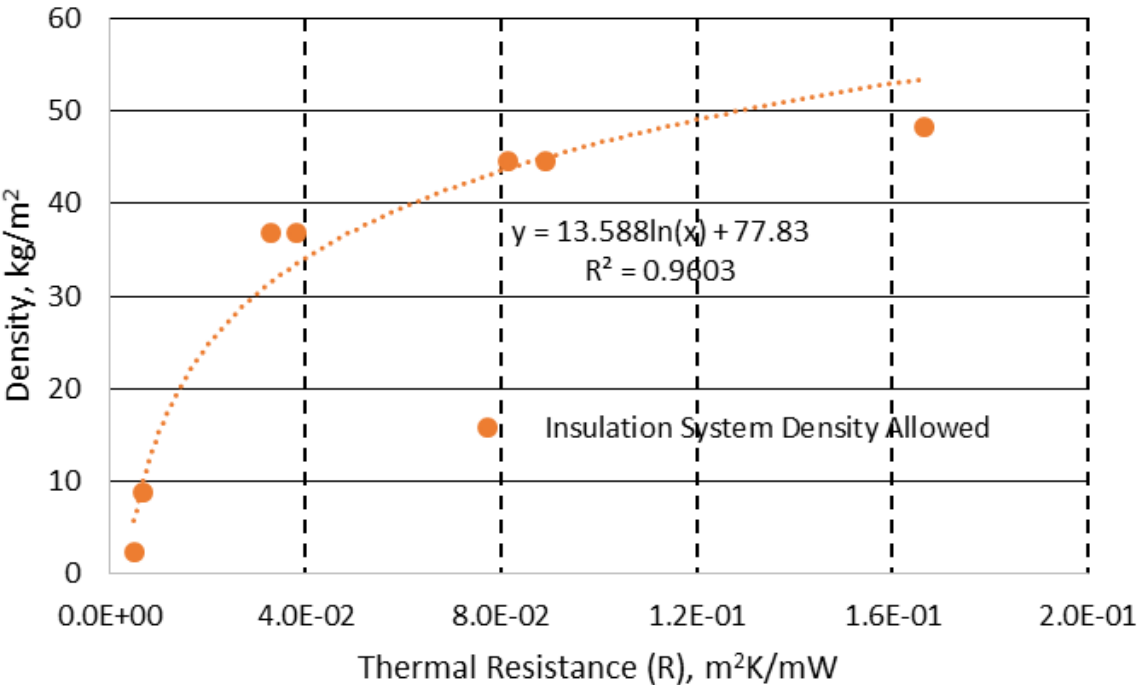
Process

- Initial calculations were done using a baseline thickness of 8.1 cm of foam and 5.3 cm of MLI
 - Interface temperature of 190 K
 - Heat flux of 17 W/m²
 - System mass of 1500 kg
- Substitute non-descript insulation system (R-value) for SOFI
 - Assume a thermal conductivity and thickness
 - Calculate thermal resistance
 - Maintain MLI for in-space protection
 - Resize refrigeration and heat rejection system
- Lower mass of smaller refrigeration system allows for insulation mass growth
 - Constant thermal system mass

Case	CBT	k -subst.	x - subst.	Ti	x MLI	WBT	R	Q	Qtot
	K	mW/m-K	m	K	m	K	m ² K/mW	W/m ²	W
1	105	1.0	0.033	250	0.05334	267	3.30E-02	4.39	645
2	105	1.0	0.081	260	0.05334	267	8.13E-02	1.91	273
3	105	0.2	0.008	250	0.05334	267	3.81E-02	3.81	645
4	105	0.2	0.018	260	0.05334	267	8.89E-02	1.74	273
5	105	0.2	0.033	263.5	0.05334	267	1.66E-01	0.95	142.9
6	105	5.0	0.033	203	0.05334	267	6.60E-03	14.84	2225.9
7	105	16.4	0.081	190	0.05334	267	4.96E-03	17.15	2453



Results



Case	Thermal Resistance m²K/mW	Maximum Insulation mass allowed kg	Maximum Insulation Areal Density kg/m2
1	3.30E-02	1058	36.91
2	8.13E-02	1276	44.52
3	3.81E-02	1058	36.91
4	8.89E-02	1278	44.52
5	1.66E-01	1384	48.29
6	6.60E-03	254	8.86
7	4.96E-03	68	2.37

Mass gains come from insulation systems under the curve



Vacuum Jacket Sizing

- The ultimate insulation solution would be a “light-weight” vacuum jacket
- Historically vacuum jackets sized to provide ~ 1 atmosphere compression strength
 - For the tank size evaluated, this was several tons of mass total
 - Does not trade favorably to mass of refrigeration delta from baseline
- “Lightweight” vacuum jacket concept
 - NASA has had multiple technology development programs dating back to the 1970s investigate lightweight, 1 atmosphere vacuum jackets
 - All have failed, mainly due to leakage/sealing/permeation issues due to straying from solid metallic vacuum vessels
 - Designing for a 5 Torr compression pressure allows the metallic jacket to be on the order of 0.075” or possibly less. This has a mass penalty of around 700 kg, which coupled with a high performing insulation system could provide mass benefits.
 - There is a catch: the vacuum jacket has to survive launch, which means it will start filled with gas (probably nitrogen). It would then be evacuated during the transit stage and have to be isolated before descent to Mars.
 - This implies that there is now a reliability/operational issue in addition to the thin wall vacuum jacket



Conclusions

- The mass of the liquefaction system could be significantly reduced, could it be integrated onto the MAV flight tanks
 - Alternatively other “free” tanks could be investigated (other propulsion system tanks brought to the surface such as on descent module)
 - Flight weight cryocoolers with lift at ~ 90 K an order of magnitude more than has been developed will probably be needed
- Further investigation into in-tank liquefaction processes needed to verify system performance and identify performance drivers
- A trade between cryocooler mass and insulation performance gives some development targets for insulation on the Martian surface
 - There is the possibility of significant mass savings from the development of either Mars atmospheric vacuum jackets or other high performance soft vacuum insulation systems
 - Operational development of “lightweight” vacuum jackets will need some development